AN EXAMINATION OF GREEN ROOF PLANT SELECTION AND DESIGN TO OPTIMIZE FOR EVAPOTRANSPIRATION

A Thesis

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ABSTRACT

Green roofs are a new and growing field in North America. Along with the need for innovation in design, research on green roof systems and performance is necessary to capture and improve the way in which green roofs function. Green roof performance and benefits have traditionally been measured by their ability to capture storm water, cool the building below it by means of shading and evaporative cooling, and their ability to successfully support plant life. Currently, green roofs design is dominated by shallow, light weight substrates and extremely drought tolerant plants, often from the *Crassulaceae.* This design predilection is based upon the limiting factors of building loading limits and installation costs. However, this design negates most of the benefits green roofs are expected to provide. Water holding capacity, and thus the green roof's ability to retain significant volumes of storm water, is contingent on the depth of the substrate. By selecting plant species which are highly drought tolerant, the evapotranspiration rates are reduced. Additionally, many members of the *Crassulaceae* have an inverted stomatal rhythm wherein stomates are open at night to permit gas exchange with the atmosphere when transpirational demand is low and when cooling of the building is less needed. Therefore, a shift in focus is necessary, in which the design of green roofs is based on optimizing the performance of desired benefits. While limitations in cost and loading must be accounted for, they should not be the driving force of green roof design.

In response to this issue, this thesis examines an alternative approach to conceptualizing and designing green roofs. The following research presents a green roof system that held all storm water to the point of full saturation. Additionally, plant species capable of withstanding both drought and flooding were placed in a green roof setting. Evapotranspiration rates were recorded for *Solidago canadensis* and *Spartina alterniflora* during the summer of 2005, applying measured volumes of water to test

the system’s ability to hold large volumes of water as well as the rate at which this water could be used by the plants. Full capacity of the substrate averaged approximately a 2-year return frequency storm for New York City, at 3 inches of water over a 24 hour period. Both plant species were capable of consuming enough water to shift from saturation to no levels of standing water within 4 days, suggesting the system’s ability to withstand several rain events in succession. The rates of evapotranspiration slowed as less water was present in the substrate, suggesting that the plant species could survive a prolonged period of drought by adjusting water usage. By storing greater volumes of water within the substrate, larger volumes of water were made available to the plant, reducing the need for more frequent rainfalls.

Ultimately, this system exhibits a tolerance of drought and flooding and provides greater opportunity for plant survival, as compared to a freely draining, more drought-prone green roof design approach. While the studies conducted were for small units embedded within a larger green roof, and data was collected for a short period, the results suggest that this approach has immense potential in improving green roof benefits, and warrants further study.

BIOGRAPHICAL SKETCH

Jeannette Compton was born in New Haven, CT on March 3, 1983. Being the 5th Jeannette in a row, with four of the five around when she was growing up, a switch to the nickname Nette was in order simply to prevent confusion. While growing up, she was always interested in the natural world, and could often be found climbing trees, observing, and playing in the dirt. Gardening was a standard summer activity, and her parents and grandparents instilled in her an interest in gardening, compost, as well as capturing nature through art. All of this had a lasting impression on her, and she can still be found doing any number of these activities.

When it came time for Nette to grow up and decide what to do with her life, the ideal combination of the horticulture and art led her to pursue landscape architecture at Cornell University. Despite blizzards and many long hours in studio, she managed to enjoy herself, yet was not satisfied with landscape architecture alone. Adding on a major in plant science and focusing on sustainable design became interests later on in her undergraduate career. Having spent past summers working for the parks department, an engineering firm, and a plant nursery, it became increasingly clear that the most successful landscape architecture comes from integrating other fields with design.

All of these interests led to a decision to stay in school at Cornell, working towards a Masters degree in horticulture while simultaneously taking advantage of Cornell's diverse departments, including environmental engineering and city planning. Selecting a thesis project was the most difficult part, as there were so many interesting topics to focus on. After finally deciding on green roofs, Nette has enjoyed studying such a fast growing and exciting topic, and will hopefully one day save the world.

To the long line of Jeanettes before me, who have all been constant sources of inspiration and strength.

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Beyond the functional assistance from all the people I collaborated with in completing my graduate work, I would like to thank all of the people who served as moral support along the way. This especially goes to my mother, Jeanette, who has not only encouraged me throughout all of my schooling, but served as a wonderful example herself. And of course, to Josh Price, who has valiantly tolerated all that I manage to throw at him. He has made my time in graduate school one of the best times in my life, and everything save finishing my thesis was possible thanks to him.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER ONE

LITERATURE REVIEW

Current Status of Green Roof Research

The concept of growing vegetation on a rooftop is not a new phenomenon but now is an old solution applied to a new problem. In Europe, mosses and other plant materials have been deliberately grown on roofs for centuries, serving purposes as diverse as fire retardants and herb gardens (Koehler, 2003; Garbutt, 2005). In other cases, rooftop vegetation simply volunteered. A waterworks in Switzerland built in 1914 used soil on its rooftop to cool the building below, allowing a diverse meadow to form from wind-borne propagules. But it was not until the 1970's that green roofs began to be valued as functional components of the urban landscape. In Germany, Sweden and other northern European countries, green roofs began to be seen as a viable means of increasing the amount of vegetation in cities, where open space at ground level is limited but roof tops are largely unused (Koehler, 2003). As popularity and understanding of green roofs grew, their ability to contend with urban issues beyond provision of green space became apparent. Green roofs are capable of retaining storm water, cooling buildings and other functions that are now the focus of long term studies of new and existing roofs (Koehler, 2003). An increase in green roof support has resulted from an understanding of the capacity for green roofs to alleviate some of these urban problems.

While accepted and popular in Europe, in North America green roofs have been slow to gain popularity. One major obstacle to widespread use of green roofs is concern about their cost relative to their benefits. As a new technology, higher costs related to products and installation act as a barrier in their widespread use. Green roofs are further hindered by a lack of accurate data on performance, especially data specific to North American climates. However, this is becoming less the case as green roof popularity and research increases. Benefits to building owners are better understood, including decreased cooling demand in summer months, increased roof longevity, and aesthetic improvement. Models comparing green roofs to traditional flat roofs have shown decreased energy costs related to heating and cooling, reducing daily energy demands for space conditioning by as much as 75% during the summer (Liu, 2004; Liu and Minor, 2005). Green roofs decrease the impacts of heat aging on roofing materials by protecting them from UV radiation and temperature fluctuations (Liu 2004). In addition to a better quantification of the cost savings resulting from green roofs, their initial cost of installation is on the decline. Green roof infrastructure and product availability have grown in past years in response to demand, and today a much wider variety of materials are available at lower costs. As the argument for green roofs is strengthened by more concrete evidence of their benefits, the economic barrier of installation has been simultaneously reduced.

Due to green roofs' ability provide benefits beyond the immediate buildings they are housed on, they have become appealing to municipalities. While the aesthetic and ecological aspects of green roofs are appealing, cities have also embraced green roofs due to several economically based incentives such as municipal storm water management. With extensive impervious area, polluted waters, and high cost of treating large volumes of storm water, many cities have had difficulties in meeting rising water quality standards. Green roofs offer an alternative to traditional storm water management techniques that is feasible in urban areas, retaining storm water on site and preventing it from entering a city sewer (Graham and Kim, 2003; Moran et al., 2005). In addition, green roofs on a large scale may offer heat island mitigation in the summer by reducing heat flow as well as actively cooling the air as plants evapotranspire (Liu, 2004).

These capabilities have resulted in cities and federal governments encouraging or enforcing the development of green roofs. 43 percent of German cities have policies promoting green roofs, and the country also requires green roofs to be included in some greenfield development (Garbutt, 2005). Green roofs have become one of the main components in Chicago's initiative to become the "greenest city" in the United States. The city's efforts include many government buildings with green roofs already outfitted or scheduled to be installed soon. According to the city's Department of Environment website, more than 1 million square feet of green roofs were in place or in the process of being installed on over 80 municipal and private green roofs in Chicago as of June 2004. Other cities in North America have proposed similar initiatives, including Toronto, ON and Portland, OR.

One of the aspects of green roofs that make them so appealing is their ability to use solar energy to provide services such as cooling and storm water retention at little cost beyond installation. Yet the fact that green roofs use living plants to dissipate energy and runoff also means that they are influenced by environmental variation in temperature and precipitation. And while there is research available on roofs in European climates, this does not necessarily transfer well to North America. Even within North America, climatic variation limits our ability to generalize on performance. Plant selection and roof performance can vary greatly across regions, creating a need for roof performance data to relate to climate as well as design specifics of the roof.

Much of the current green roof research occurring in North American fittingly centers on roof function and benefits (Graham and Kim, 2003; Liu, 2004; Moran et al., 2004; Brenneisen, 2005; Carter and Rasmussen, 2005; Gaffin et al., 2005; Liu and Minor, 2005; Rosenweig et al., 2006). Universities, municipalities and non-profit organizations have examined individual roofs and created models in pursuit of describing the green roof (Hutchinson et al.; 2003; Dvorak, 2004; Earth Pledge, 2005; LaBerge et al., 2005). This research looks to characterize the types of green roof systems that are most popular; those with shallow, light weight substrate and drought tolerant succulent plant species such as *Sedum spp.* The design criterion for these roofs focuses on minimizing costs and maintenance. The research surrounding this approach then focuses on optimizing for these two priorities, though testing shallow soils (Nektarioset al., 2003; VanWoert et al., 2005) and the most drought tolerant plants (Durhman et al., 2004; Rowe et al., 2005).

The limited depth of media on most green roofs stems from concerns over loading capacity and a desire to minimize installation costs (Boivin et al., 2001; Durhman et al., 2004; Monterusso et al., 2005; Rowe et al., 2005; VanWoert et al., 2005b). However, shallow soil restricts the amount of water available for plants and can lead to drought conditions throughout much of the growing season. While the media components maximize water retention per unit volume, the total volume that can be retained in a shallow depth is necessarily quite small (Liu 2004). VanWoert et al. studied moisture levels of substrate receiving measured applications of irrigation (2005b), finding that media reached 0 m^3*m^{-3} within as little as one day between watering. While irrigation was minimal and the substrates were as shallow as 2cm with or without water retention fabric below, the study reflects how extreme growing conditions can become on an extensive green roof. Additional studies of *Sedum* and other species displayed similar growing conditions and showed how this greatly limits plant selection (Durhman et al., 2004; Monterusso et al., 2005). Shallow media depths lead to the exclusive use of highly stress tolerant plants, which in turn have low evapotranspiration rates (VanWoert et al., 2005b). The impacts of this tendency in green roof design on plant selection will be discussed in detail later on in the paper.

The green roof is also expected to accomplish the maximum possible benefit in storm water retention, using this water to cool the building as it is evapotranspired. The expectations of green roof performance and the parameters within which they are designed are in direct contradiction. While lowering costs and maintenance decrease economic barriers of green roof application, a building owner cannot accrue the initial cost of the installation back if the green roof fails to provide the savings that are touted as the payback. As I will show, the net effect is that the derived benefits of storm water retention and evaporative dissipation, as well as evaporative cooling are largely negated.

Storm Water Management

Storm water attenuation is one of the green roof's much cited benefits but has raised concerns about leakage of water impounded on a roof. However, this objection is quelled by the fact that green roofs use the same waterproofing methods of conventional roofs, often using more waterproofing material than required as added assurance. Beyond leakage, structural reinforcement needs have been raised as objections, especially for retrofits on existing buildings. Green roofs undeniably add extra weight to buildings in the form of growing medium, vegetation, and most significantly, water. Efforts to reduce loading have included replacing soil with light-weight growing media specifically designed for green roofs, as well as general limitations on substrate depth. The depth of the substrate has a significant impact on its weight as well as its water holding capacity (Rowe et al., 2003; VanWoert et al., 2005a). Yet by limiting the amount of water contained within a green roof system, the water retained from rain events and then available to plants to grow and cool the roof is in turn limited.

Green roof storm water attenuation and runoff, both in the total volume and rate of runoff, can have an impact on a city's storm water system. A green roof is capable of retaining and removing some storm water from the sewer system as well as delaying runoff peak flows, alleviating the overflows that can result in combined sewer outflows at sewage treatment plants (Hutchinson et al, 2003; Liu, 2004; LaBerge et al., 2005; Liu and Minor, 2005; VanWoert et al., 2005a). Monitoring studies at a number of test sites across the continent reflect a wide range of climatic conditions as well as variation among roof design (Table 1-1). Variations in retention rates among studies are influenced by rainfall patterns in different regions, length and season of the study, and depth of the media (Table 1-1).

These studies showed several consistent patterns. While there was a consensus among researchers that green roofs retained all or most of smaller storms (Rowe et al., 2003; LaBerge et al., 2005; Liu and Minor, 2005), what qualified as a smaller storm ranged from less than 2mm (Rowe et al., 2003) to less than 0.3 inches (LaBerge et al., 2005). Performance during larger rain events varied by frequency of storms and season, as well as by the design of the roof itself (Hutchinson et al., 2003, LaBerge et al., 2005). Where these rates were compared to a conventional roof, green roofs had a significantly higher retention rate (Liu and Minor, 2005). While Rowe et al. found that 100% vegetative cover of substrate yielded 3% greater storm water retention than non-vegetated substrate in 2003, VanWoert et al. concluded that roofs with substrate were able to retain more rainfall than conventional roofs, regardless of vegetation (2005). Rowe et al. (2003) and VanWoert et al (2005a) have studied how runoff rates are impacted by slope, vegetation, and substrate type and depth, showing that shallower slopes capture more storm water. Mentens et al. (2003) have found that degree of slope and orientation of sloped roofs have an impact on evapotranspiration and thus water holding capacity, through models based on earlier research. Beyond retention of storm water, Hutchinson et al. (2003), Liu and Minor (2005), and Moran et al. (2004, 2005) found that peak flows were delayed and reduced regardless of storm intensity.

While all of these studies depict the behavior of the test site during a set period of time, few comparisons to weather patterns or standard storm water design volumes were made, making it difficult to extrapolate the data beyond the specific parameters of each study. Hutchinson et al. (2003) considered the impact of daily temperatures and rainfall frequency had on potential evapotranspiration and retention rates. The green roof's performance was also examined during a 2 year, 24 hour storm, providing information that is more readily transferable, and compares performance to engineering standards. The study also provides information on typical rainfall rates in the area over the past 5 years, better relating the performance of the green roof to a typical Portland, OR growing season and allowing estimations of storm water retention in future green roof designs. The addition of weather data such as potential evaporation, temperature and other meteorological factors that impact water use would provide an even more accurate picture.

While green roofs have been shown to be an asset in storm water management for their retention capacity, they do not contain every storm and thus produce runoff. While this runoff comes in reduced and delayed peak flows, it may still pose water quality problems. As rainwater drains through the growing medium, is water filtered or have contaminants been added? Hutchinson et al. (2003) sampled runoff from green roofs and found concentrations above the water quality standards of Portland, OR for total phosphorous and ortho-phosphate; although no comparison of conventional roof runoff was made. It was also found that during the drier summer months when phosphorus is more of a concern in the area, the concentrations leaving the green roof were lower. Moran et al. (2004, 2005) found runoff from green roofs tested higher in total nitrogen and total phosphorus levels than a control roof, and speculated that runoff was impacted by the substrate's composition, which included 15% compost. Hutchinson cited attention to substrate components as a means of managing runoff concentrations, and preliminary testing of green roof media by Moran indicated that a reduction in organic matter would reduce the leaching of nitrogen and phosphorus.

Retention rates and water quality data provide information on the performance of individual roofs and permit speculation on their positive impacts on storm water management within its specific footprint. Beyond this, other studies attempt to characterize how green roofs may also be capable of impacting entire watersheds. A model of the Greater Vancouver Region watersheds examined the impacts of green roof retrofits over a 50 year span, and estimated that green roofs could provide significant improvements on the watershed's ability to handle storm water, effectively counteracting increases in high-density land use (Graham and Kim, 2003). The study found that substrate depths of 10 cm were capable of reducing runoff rates from short, high intensity storms occurring during dry weather. Increases in depth improved a roof's ability to retain storm water, finding that 25 to 30 cm substrate provides optimal retention rates of even prolonged winter storms typical to the area.

Carter and Rasmussen (2005) studied storm water flows from green roof test plots and applied the data to a spatial analysis of the Tanyard Branch watershed in Athens, GA to model city-wide green roof implementation. The highly-urbanized region consists of 54% impervious surfaces, with 16% of the total area comprised of rooftop. The model compared existing conditions with the effects of all roofs or all flat roofs being converted to green, and studied 24 hour storms with 1 year, 25 years, and 100 years return frequencies. The study concluded that green roofs have the ability to impact watersheds, but mainly in smaller rain events, below a 1 year storm.

Applying green roofs to all flat buildings would reduce the runoff of the entire watershed by 7%, 4% and 3% respectively for a 1, 25 and 100 year storm. While the impacts on larger storms are small, this change is achieved by only manipulating the 30% of impervious surfaces comprised of roofs. The authors speculate that in denser areas, green roofs could have more wide-spread impacts on a watershed. Graham and Kim (2003) state that green roofs, in conjunction with rain cisterns and infiltration facilities are capable of making significant improvements in the quality and quantity of runoff. However, this study does not indicate the degree to which these techniques are capable of achieving this, or whether additional methods would be necessary to achieve water quality goals for the watershed.

Thermal Performance

Buildings are dependent on outside energy to maintain comfortable interior temperatures, with dark roofing membranes absorbing solar energy capable of reaching over 150ºF during the summer (Lui and Baskaran, 2003). The "urban heat island effect" states that cities have elevated temperatures in relation to the less urbanized areas surrounding them (Bass et al., 2003; Lui and Minor, 2005). One approach to reducing buildings heat load and heat absorption would be to switch roofing surfaces from black materials to white (Gaffin et al, 2005). Green roofs provide a piece of naturally functioning landscape (Brenneisen, 2005), and can provide significant benefits for a building as well as the surrounding area. Leonard and Leonard (2005) found a 16% reduction in energy demand from cooling units for buildings with green roofs during a sample week during a summer in Minnesota. Lui (2004) found a 75% reduction in daily energy demand for space conditioning in a test building in Toronto. Beyond the passive methods of reflecting sunlight and utilizing it for photosynthesis while shading the building, green roofs can actively cool the roof as water is transpired by plants cooling the surrounding air (Liu, 2004; Liu and Minor, 2005). An urban area can begin to shift towards a natural system by employing green roofs on a city scale (Rosenzweig et al., 2006).

Several green roof studies have examined just how different a green roof performs in comparison to both conventional and white roofs. Green roofs are quite successful at moderating temperature extremes but are far more successful in the summer than the winter (Liu, 2004, Liu and Minor, 2005). Peak temperatures during the day are lowered and also delayed in comparison to the other roofing materials studied; by how much is a matter of climate and individual studies. Lui (2004) found a 95% reduction in heat gain on a test roof in Toronto. Using data from a study of green and white reflective roofs, Gaffin et al. (2005) estimated that in order for a white roof to cool as well as a green roof, the maximum reflective products available would be necessary. The albedo range of 0.7-0.85 needed would require constant maintenance and replacement in order to maintain performance comparable to a green roof. LaBerge et al. (2005) found little difference in the mean daily maximum temperatures at the rooftop surface between the white reflective roof, stone roof, and green roof. However, at the roofing membrane layer, the temperature of the black tar, white reflective and stone roofs were a standard deviation above the green roof's mean. The difference between the rooftop and membrane horizons suggests a difference between the passive shading and active cooling of the roof through water loss. The depth of the green roof growing medium was not provided, so it is difficult to gauge the type of green roof needed to achieve similar results. Although the membrane temperature fluctuations better reflect the energy flow to the interior of the building, they do not necessarily indicate a significant change on building energy demand. Further studies on green roof energy performance might center on the energy consumption differences, and how the design of a green roof could optimize its cooling benefits.

This data would allow for estimations of cost savings for proposed green roofs based on climate and design.

A comparison of energy demand of buildings with different roofing surfaces has been performed at a test roof in Ottawa, Canada. Liu (2004) compared the performance of black and green roofs on a building with a roof divided in half with both roofing types. It was found that green roofs not only reduced the mean temperature and temperature fluctuation of the roofing surface and membrane below, but they also reduced heat flow into the building. The green roof, with a soil depth of 150 mm (6 inches), reduced peak roof membrane temperatures by 40ºC and reduced the temperature fluctuations in the spring and summer from a range of 45ºC to a range of 6ºC. A shift from a demand of 6.0-7.5kWh/day to less that 1.5kWh/day and a reduction in the demand for space conditioning by 75% was found between the black tar roof and the green roof. Leonard and Leonard (2005) compared white, black and green roofs in Minnesota. The study considered the green roof's ability to provide the benefits of a reflective roof without glare, finding that with immature plants and thus low evapotranspiration rates, the roofs performed similarly. The authors speculate that with plant maturity the green roof could surpass the white roof, as well as avoiding glare. This study also examined the trade off of having cooler roofs in the winter, and found that although black roofs were slightly warmer in winter, the differences were less than in the summer, and the summer energy savings outweighed the winter energy gain of the black roof.

Beyond the energy savings and benefits to an individual building, green roofs on a city-wide scale may reduce temperatures across urban areas. A study in Toronto modeled green roof impacts on typical summer days (Bass et al. 2003). Assuming 50% of the city's available rooftops would be planted as grassland with an unspecified medium depth, the study estimated that green roofs on a city wide scale could result in

0.1-0.8ºC cooling throughout the city. A climatic study of the New York City region examined a variety of techniques to mitigate city's heat island, including green roofs (Rosenzweig et al., 2006). Using data from several heat waves in the city during 2002 and assuming 100% of the available area could be converted to green infrastructure, the study estimated the reduction of near surface temperature. Converting all roof area to green roofs was found to be comparable to converting all available street areas to tree plantings, reducing temperature nearby by 0.6 and 0.7ºC respectively. The study recommended using both green roofs and street tree plantings, but noted that green roofs may be more practical in dense neighborhoods that lack space for street planting. The study also compared combinations of several techniques, and suggested that the most effective means for reducing temperatures throughout the day would be to convert open grass and curbside areas to street tree plantings and rooftops to green roofs, reducing temperatures by approximately 1.6ºC across the city. This study indicated the abilities of green infrastructure to mitigate urban heat islands, but also how widespread the application of this infrastructure would need to be.

Plant Selection and Biodiversity

The conditions required for plant growth are solar radiation, water, nutrients, oxygen, carbon dioxide and a rooting medium. Sun and water are for the most part fixed conditions on green roofs, but artificial rooting media can be selected to provide physical support, retain water and provide nutrients. With loading and water holding abilities emphasized, a green roof growing medium has many demands which need to be satisfied. Lightweight mixtures consisting of materials such as peat, perlite, foam, heat-expanded shale, sand, and compost (Nektarioset al., 2003; VanWoert et al., 2005b) have been favored over topsoil (Table 1-3). Beyond the components, depth of the media has great influence on plant growth. As shown in studies of green roof vegetation examine plant growth at depths as shallow as 2 cm (Durhman et al., 2004; VanWoert et al., 2005b), but most commonly range between 5 and 15 cm (Boivin et al., 2001; Durhman et al., 2004; Dvorak, 2004; Monterusso et al., 2005; Rowe et al., 2005; VanWoert et al., 2005b). Such shallow depths can create water-limited environments, as acknowledged in most of these studies. In plots receiving rainfall, soil moisture content averaged 0.1 m^3*m^{-3} (Monterusso et al., 2005). In a study of set irrigation periods (VanWoert et al., 2005b), soil moisture stayed below 0.25 m^3*m^{-3} in plots watered every 2 days, with plots receiving irrigation more than 5 days apart dropping to zero percent moisture content.

The ability of *Sedum* species to survive the extreme drought conditions of shallow growing medium and limited water has been well documented (Durhman et al., 2004; Monterusso et al., 2005; VanWoert et al 2005b). While these plants survive the stringent conditions imposed by the average green roof, this should not be interpreted to mean that *Sedum* is capable of providing the ecological services imputed to green roofs. By concentrating on the most drought tolerant plants able to survive the most extreme conditions (Monterusso et al., 2005; VanWoert et al., 2005b), plants with greater potential for evapotranspiration, and thus evaporative cooling and runoff reduction have been ignored. While current research simply explores plant survival, alternative designs that optimize plant performance warrant consideration. Adding media depth adds weight to the roof but is certainly possible, as evidenced by green roof plantings in far deeper medium than commonly studied (Earth Pledge, 2005). VanWoert et al. (2005b) showed evapotranspiration (ET) rates of irrigated green roof test plots for plots irrigated every 2 or 7 days. Some plots irrigated every 7 days had no net water loss on the 4th day after receiving water. All plots had zero ET by the 7th day. This implies that for many green roofs, evaporative cooling is only possible if rainfall occurs more than once a week; not likely in warm summer months in many climates. Shallow substrate containing small amounts of water coupled with plants highly efficient in water use yields a system that does not optimize for evaporative cooling in any way. Thicker substrates that attenuate greater volumes of water also allow for plants with higher evapotranspiration rates and greater potential for cooling. An additional benefit is access to a greater variety of plants, including possibilities of native plantings.

Conclusion

Green roofs have great potential, and this potential can only be expanded through new and innovative thinking. Many current writings on environmental issues and solutions cite the need to return to nature for inspiration, successful design, and more holistic thinking. Green roofs provide vast improvements over conventional systems, but this improvement can be optimized further still. By expanding and improving the approach of green roof design, the benefits of green roofs may be greatly increased.

Study Name	Location of Trial	Length of Trial	Retention	depth of media (cm)
Carter and Rasmussen 2005	Georgia, USA	1 year	78%	not available
Hutchinson et al. 2003	Portland, OR, USA	15 months	69%	11.0
LaBerge et al. 2005	Chicago, IL, USA	1 year	61%	not available
Liu 2004	Toronto, ON, CA	spring & summer	54%	15.0
Liu and Minor 2005	Toronto, ON, CA	1 year	57%	8.6
Moran et al. 2004	North Carolina, USA	April - Dec	62%	7.5
Moran et al. 2004	North Carolina, USA	July-August, Nov-Dec	63%	10.0
Moran et al. 2005	North Carolina, USA	18 months	63%	7.5
Moran et al. 2005	North Carolina, USA	July-Sept	55%	10.0
Rowe et al. 2003	Michigan, USA	Sept-Oct and March	66%	4.5
VanWoert et al. 2005a	Michigan, USA	14 months	60%	5.5
		Average	63%	8.8

Table 1-1: Retention Rates from Various Green Roof Studies

Table 1-2: Substrate Constituents for Green Roof Growing Media

Media Type	% by Vol., Depth of Media (Study Name)
Coarse Peat Moss	15%, 3 in. (Hutchinson et al., 2003)
Compost	15%, 3 in. (Hutchinson et al., 2003); 10%, 5 in. (Hutchinson et al., 2003); 3.3%, 1-2.4 in. (Rowe et al., 2003; Durhman et al., 2004; VanWoert et al., 2005b); 15%, 4 in. (Moran et al., 2004, 2005); 5%, 4 in. (Monterusso et al., 2005; Rowe et al., 2005)
Digested Fiber	15%, 3 in. (Hutchinson et al., 2003); 20%, 5 in. (Hutchinson et al., 2003)
Dolomite	5%, 1-2.4 in. (Rowe et al., 2003; Durhman et al., 2004; VanWoert et al., 2005b)
Encapsulated Styrofoam	25%, 3 in. (Hutchinson et al., 2003)
Heat Expanded Shale	40%, 1-2.4 in. (Rowe et al., 2003; Durhman et al., 2004; VanWoert et al., 2005b); 55%, 4 in. (Moran et al., 2004; 2005); 60%, 4 in. (Monterusso et al., 2005; Rowe et al., 2005)
Michigan Peat	10%, 1-2.4 in. (Rowe et al., 2003; Durhman et al., 2004; VanWoert et al., 2005b); 10%, 4 in. (Monterusso et al., 2005; Rowe et al., 2005)
Mineral Aggregates	60%, 2-6 in. (Boivin et al., 2001)
Organic Matter	40%, 2-6 in. (Boivin et al., 2001)
Peat	0-30%, 16 in. (Nektarios et al., 2003)
Perlite	15%, 3 in. (Hutchinson et al., 2003); 22%, 5 in. (Hutchinson et al., 2003); 0-20%, 16 in. (Nektarios et al., 2003)
Resin Foam	0-40%, 16 in. (Nektarios et al., 2003)
Sand	30%, 4 in. (Moran et al., 2004; 2005)
Sandy Loam	28%, 5 in. (Hutchinson et al., 2003); 50-100%, 16 in. (Nektarios et al., 2003)
Turkey Litter	1.67%, 1-2.4 in. (Rowe et al., 2003; Durhman et al., 2004; VanWoert et al., 2005b)
USGA Grade Sand	40%, 1-2.4 in. (Rowe et al., 2003; Durhman et al., 2004; VanWoert et al., 2005b); 25%, 4 in. (Monterusso et al., 2005; Rowe et al., 2005)

Table 1-3: Plant Species and Substrate Depths Found in North American Green Roofs

Plant Species	**Depth of Substrate Grown in (Study Cited)**
Ajuga reptans	5-15 cm (Boivin et al., 2001)
Allium cernuum	10 cm (Rowe et al., 2005; Monterusso et al., 2005)
Arenaria verna	5-15 cm (Boivin et al., 2001)
Armeria maritima	5-15 cm (Boivin et al., 2001)
Coreopsis lanceolata	10 cm (Rowe et al., 2005; Monterusso et al., 2005)
Delosperma cooperi	5-10 cm (Moran et al., 2004)
Delosperma nubigenum	5-10 cm (Moran et al., 2004), 7.5 cm (Moran et al., 2005), 10 cm (Moran et al., 2005)
Draba aizoides	5-15 cm (Boivin et al., 2001)
Gypsophila repens	5-15 cm (Boivin et al., 2001)
Opuntia humifusa	10 cm (Rowe et al., 2005; Monterusso et al., 2005)
Saxifraga granulata	4.5 cm (Rowe et al., 2003)
Sedum acre	2.5-6 cm (VanWoert et al., 2005a), 3.75 cm (VanWoert et al., 2005b), 2.5-7.5 (Durhman et al., 2004), 10 cm (Rowe et al., 2005; Monterusso et al., 2005)
Sedum album	2.5-6 cm (VanWoert et al., 2005a), 3.75 cm (VanWoert et al., 2005b), 2.5-7.5 (Durhman et al., 2004), 10 cm (Rowe et al., 2005; Monterusso et al., 2005), 10 cm (Moran et al., 2004), 5-10 cm (Moran et al., 2004), 7.5 cm (Moran et al., 2005)
Sedum album chloroticum	5-10 cm (Moran et al., 2004)
Sedum album murale	10 cm (Moran et al., 2004), 5-10 cm (Moran et al., 2004), 7.5 cm (Moran et al., 2005), 10 cm (Moran et al., 2005)
Sedum ellacombeanum	10 cm (Rowe et al., 2005; Monterusso et al., 2005)
Sedum floriferum	10 cm (Moran et al., 2004), 10 cm (Moran et al., 2005)
Sedum grisebachil	5-10 cm (Moran et al., 2004)
Sedum kamtschticum	10 cm (Moran et al., 2005)
Sedum kamtschticum ellacombianum	2.5-6 cm (VanWoert et al., 2005a), 3.75 cm (VanWoert et al., 2005b), 10 cm (Rowe et al., 2005; Monterusso et al., 2005)
Sedum mexicanum	2.5-7.5 (Durhman et al., 2004)
Sedum middendorffianum	10 cm (Rowe et al., 2005; Monterusso et al., 2005)
Sedum pulchellum	2.5-6 cm (VanWoert et al., 2005a), 3.75 cm (VanWoert et al., 2005b), 10 cm (Rowe et al., 2005; Monterusso et al., 2005)
Sedum reflexum	2.5-6 cm (VanWoert et al., 2005a), 3.75 cm (VanWoert et al., 2005b), 10 cm (Rowe et al., 2005; Monterusso et al., 2005), 10 cm (Moran et al., 2004), 5-10 cm (Moran et al., 2004), 7.5 cm (Moran et al., 2005), 10 cm (Moran et al., 2005)
Sedum sexangulare	10 cm (Moran et al., 2004), 5-10 cm (Moran et al., 2004), 7.5 cm (Moran et al., 2005), 10 cm (Moran et al., 2005)
Sedum spp.	4.5 cm (Rowe et al., 2003)
Sedum spurium	2.5-6 cm (VanWoert et al., 2005a), 3.75 cm (VanWoert et al., 2005b), 10 cm (Rowe et al., 2005; Monterusso et al., 2005)
Sedum spurium fuldaglut	5-10 cm (Moran et al., 2004)
Sedum x hybridum	5-15 cm (Boivin et al., 2001)
Tradescantia ohioensis	10 cm (Rowe et al., 2005; Monterusso et al., 2005)

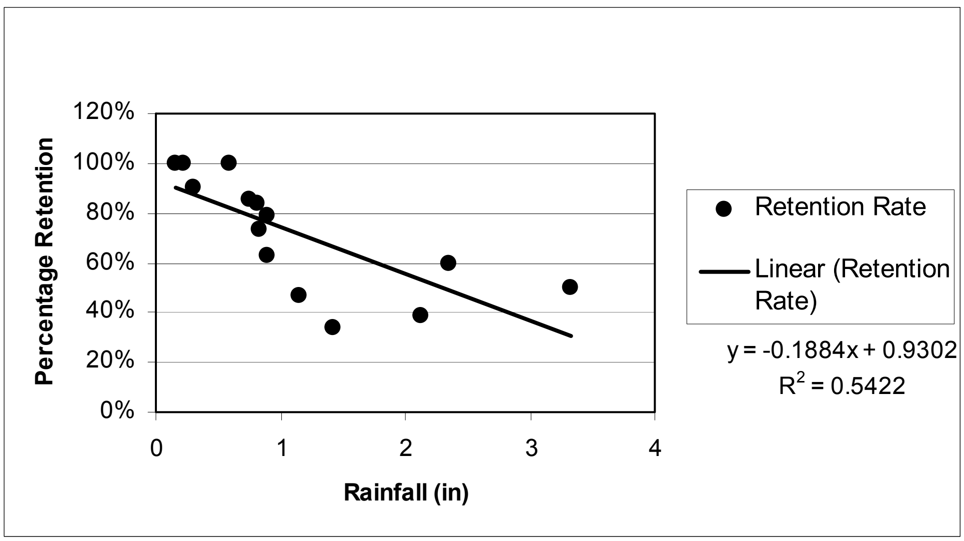

Figure 1-1: Individual Rain Event Performance for Flat Extensive Roofs in field or simulated trials

Source: Carter and Rasmussen, 2005; LaBerge et al., 2005; Liu, 2004; Liu and Minor, 2005; VanWoert et al., 2005a

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CHAPTER TWO

A ZERO DISCHARGE GREEN ROOF SYSTEM AND SPECIES SELECTION TO OPTIMIZE EVAPOTRANSPIRATION AND WATER RETENTION

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Abstract

The design of many green roofs does not optimize their potential benefits such as storm water capture and cooling through evapotranspiration. Emphasis on plant drought tolerance has led to a preference for the genus Sedum, which has a low potential for evaporative cooling as needed to provide a significant service in economic terms. Focus in research should instead be on selecting plants that will tolerate not only the extremes of green roof conditions, but also optimize evaporative cooling. Field work done on a newly installed green roof in the Bronx, NY, examined two species, *Spartina alterniflora* and *Solidago canadensis*, testing their ability to consume volumes of water equivalent to a 2-year storm. *Spartina* was selected for its tolerance of saturated conditions and in particular for its salt tolerance, with consideration for potential irrigation with grey water. *Solidago* was selected for it moderate tolerance of both drought and anaerobic (saturated) conditions. Water consumption, medium moisture, plant growth, and rates of water loss were studied in relation to weather conditions. Findings indicated that both species can tolerate the extremely dry and completely saturated conditions of the roof, as well as being capable of attenuating a 2 year storm event without drainage.

Introduction

Popularity of green roofs in urban spaces has grown in Europe and now slowly in the United States over the past 40 years (Garbutt, 2005). Green roofs are considered to provide a wide range of benefits, such as storm water capture (VanWoert et al., 2005b), increased plant variety in urban spaces (Brenneisen, 2003), roof longevity (Bass et al., 2003), urban heat island mitigation (Bass et al., 2003) and evaporative cooling of the building (Bass et al., 2003; Liu and Baskaran, 2003). However, the scientific data to justify and precisely quantify these claims lags behind this strong advocacy. What is lacking are data, such as pan evaporation and vapor pressure deficits (VPD), which allow generalization among sites and across conditions through these reference baselines (Connelly and Liu, 2005). The majority of research thus far has shown a comparison of the storm water and cooling differences between a typical urban rooftop and a green roof, but few address ways to improve the performance of the green roof system itself (Bass et al., 2003; LaBerge et al., 2005; Liu and Minor, 2005). Further research is required to quantify and expand understanding of the roof's functions and its most successful implementation strategies.

Plant selection and design of extensive green roofs are often driven by a desire to eliminate maintenance rather than optimize functional benefits (Kerner et al., 1999; Liu and Baskaran, 2003; Monterusso et al., 2005). Thin layers of media and the almost exclusive use of Sedum spp. on these green roofs provide low loading rates, good cover and a system that is highly tolerant of extreme weather and water stress conditions experienced on rooftops (Hauth and Liptan, 2003; Durhman et al., 2004; Lando, 2004; Rowe et al., 2005). Studies often test plant tolerance of extreme drought and shallow medium depth. Several of these studies establish parameters which are more extreme than those found on green roofs, unnecessarily limiting the potential for water collection by rooftops and underestimating the static loads many roofs are designed to carry. While these studies identify the most drought tolerant species, many experimental designs neither correspond to actual weather conditions in a particular area, nor reference plant performance to environmental variables such as pan evaporation, potential evapotranspiration (PE), or VPD that would allow performance to be modeled and extrapolated to other areas. Moreover, the initial assumptions of these studies rule out plant selections that may provide great cooling benefit with minimal added infrastructure or medium depth. The plants that survive such trials, typically species using Crassulean Acid Metabolism (CAM) photosynthesis and highly efficient water use, in conjunction with shallow medium, fail to provide optimal storm water attenuation or cooling of practical significance. Shifting the focus of design, away from plant hardiness and maintenance issues, would lead to systems capable of faster economic recovery of installation costs (Bass et al., 2003).

For green roofs to become a commonplace feature in American cities, economic benefits must outweigh costs, with or without governmental subsidies or enforcement. Storm water management, environmental quality and an expansion of the native plant palette in urban areas are all advantages to the municipality surrounding the roof (Deutsch, 2005). These benefits are difficult to quantify monetarily for the owner of the roof, yet greater water evaporation from storm water attenuation has the ability to increase cooling of the building, an economic benefit to the owner. While current designs allow plant survival, they are not capable of providing the maximum benefit to the owner or the surrounding area in the long term. Increasing medium depth to retain more precipitation may present itself as a concern in upfront costs as well as greater roof loading, but the gains in storm water management and evaporation rates may justify such increases. In addition, systems designed for greater storm water capture and evapotranspiration (ET) may actually increase plant survival, leading to a wider array of species as well as greater benefits from the active cooling of the roof through increased water consumption.

We investigated an alternate approach that seeks to optimize water loss through evapotranspiration. This design uses a zero discharge target, unique among green roof design. This is coupled with plant selection focused on species which tolerate both medium drought and saturation. Species selection also emphasized regional native status and salt tolerance, which would allow for the possibility of grey water irrigation. Plants were studied over a growing season to examine the rates of ET as they related to weather conditions, growing media composition saturation levels, and plant species.

Materials and Methods

Test Site. The study was conducted on top of a four story school building (St. Simon Stock School) in the South Bronx, New York City. A 3,500 square foot extensive green roof was installed during the week of June 13, 2005. The Barrett "Greenroof-Roofscape®" assembly was used, consisting of 215 mil Barrett "Ram Tough 250" monolithic rubberized asphalt membrane, polyester reinforcement, SBS (Styrene-Butadiene-Styrene) protection course, extruded polystyrene insulation, root barrier, water retention and drainage mat, and filter fabric. The substrate was comprised of approximately 10 cm of medium containing shredded polystyrene coated with pectin, compost and native clay, with a ratio of 90:10:1 by volume. Compost was mixed from agricultural waste. Atop this was another layer, comprised of bound coconut fiber, jute, and straw matting (American Green), a layer of compost and a layer of shredded wood mulch, combined a thickness of 5 cm. The test site consisted of two rows of fiberglass bins embedded in the green roof medium, with all bins receiving uniform exposure to sun and precipitation.

Planting containers. The two rows of 30.5 X 47 X 15.25 cm fiberglass tubs were installed level with the medium. Each tub contained a removable lysimeter consisting of a plastic basket 15.25 X 15.25 cm (Aquatic Ecosystems, Apopka, FL) that could be removed for weighing (Figure 2-1). A length of 3/4" Schedule 40 PVC pipe was inserted vertically into each tub as an observation well, permitting measurement of the free water depth. Each bin was lined with filter fabric and installed at a slight angle to allow drainage towards a hole drilled at one end. The hole was drilled and male adapter barbs (Aquatic Ecosystems) installed, attached to black flexible PVC tubing (Aquatic Ecosystems) which was brought to the surface and clamped shut. These permitted drainage if necessary as well as sampling leachate (Figure 2-2).

Plant material. *Spartina alterniflora* and *Solidago canadensis* were randomly assigned to the tubs (Figure 2-3). *Spartina* seed was from coastal New Jersey sources (Pinelands Nursery and Supply, Columbus, NJ) while *Solidago* seed was collected from a native stand in Tompkins County, NY. Seed was spread over the surface of 2" deep flats to achieve a density of ca 2 /cm^2 in 1:1:1 mix; peat, soil, perlite during the 3rd week of March, 2005. Later, the *Solidago* plants were moved to peat pots, 4 plants to a pot. *Spartina* seedlings were planted directly into the tubs from the flats. The bins of *Solidago* each received 9 peat pots, planted directly into the medium.

Planting medium. The research portion of the roof consisted of 12 bins with one of two medium-plant combinations assigned to 6 bins. The first medium (medium 1) was as described above for the entire roof. The other medium (medium 2) was a standard green roof substrate, consisting of 3/8 inch graded expanded shale (Norlite Corporation, Cohoes, NY), coarse ground Perlite® and agricultural waste compost in a 2:1:1 ratio by volume. Both media were mixed with the same source compost and both were installed with the same bound straw matting, compost and mulch layers as the rest of the roof.

Establishment Phase and Data Collection. Plants were allowed to establish during the period of June 22 to July 26, during which plants received ample water from rain events. Medium moisture, standing water height, ET, plant heights and weather measurements were recorded during the entire trial, including this period. Medium moisture was recorded using a soil moisture sensor (ThetaProbe Soil Moisture Sensor type ML2x, Delta-T Devices Ltd. Cambridge, UK). The probe was set to the organic soil reading and inserted at a depth of 7 cm with three measurements taken per unit, at the center and side of the bin, and outside of it. When the tubs were saturated, ET was measured as the daily difference in water depth measured through the vertical PVC tube. After the free standing water was exhausted, ET was determined as the daily difference in weight of the lysimeter baskets. Plant growth was recorded weekly, expressed as the height of the three tallest plants in each bin. Average rainfall, air temperature, atmospheric vapor pressure deficit, relative humidity, wind speed and direction and medium moisture were recorded every 5 minutes with a Campbell Scientific CR10X weather station. Evaporation was recorded with an evaporation pan (Novalynx Class A Model 255-200 with Model 255-205 stilling well and Model 255-214 hook gauge) daily throughout the growing season.

Irrigation Trials. Following the 4 week establishment period, two irrigation trials were applied beginning on July 27. No rain occurred during these trials. At the beginning of each trial volumetric water content of the substrate averaged 17.2% for Trial 1 and 22.5% for Trial 2, such that the substrate was quite dry before the application of each trial. Trial 1 consisted of applying water until each bin reached full saturation. Trial 2, beginning on August 4, consisted of applying 3 inches of water, the volume of a two year return frequency storm, or to the point of media saturation if this occurred first. The actual volume of water applied varied between trials and among experimental units (Figure 2-4). The second trial began after no standing water remained in any of the bins, as observed via the standing water measurement tubes. In Trial 1, moisture readings of the dry medium were taken before flooding. Tap water was applied in increments of 1000 ml to each bin until the medium was completely saturated, as indicated by the standing water height read from the measurement tubes reaching the same height as the surrounding medium. Medium moisture was measured immediately after flooding and then every day for the remainder of the trial. Standing water was recorded each day until no standing water remained, at which point the mass of the inner basket was measured to record water loss. The trial continued until no standing water remained in any of the bins, on August 4.

In New York City, a 2-year storm is a 3" rainfall event over 24 hours according to the New York State Storm Water Management Design Manual (New York State, 2003). One-eighth of the 3" storm volume was applied per bin each hour for 8 hours, thus applying the storm over an 8 hour period. In some of the bins, this exceeded the capacity of the bin, and water was only added until complete saturation was reached, and this volume was recorded. The mean volumes applied per substrate-species treatment are shown in Figure 2-4. Medium moisture was recorded at the end of the application, and data was recorded in the same manner as the previous trial, until August 10. The second saturation trial provided a second data set, which could be referenced to a standard weather event. Additionally, it tested the system's performance during two rain events in rapid succession.

Results and Discussion

Water Retention. By utilizing a zero-discharge system over the entire growing season, plants were able to consume all rainfall, both natural and irrigated. The water holding capacity of the bins ranged from 75% to 112% of a 2 year storm, (Figure 2-4). Differences among treatments and individual bins exist for a variety of reasons, such as pore volume of each substrate and water content at the time of irrigation. There exists a significant difference between both species and substrate, and there was no interaction between these two variables (Table 2-1). The difference in water holding capacity across media was less than between the two species, and likely reflected a difference in air filled pore space. As *Spartina* was slower to establish, treatments containing this species tended to consume water at a slower rate, leading to a moister medium at the beginning of both irrigation trials, and less pore volume available for additional water. This disparity in soil moisture was unavoidable, but by irrigating all treatments at the same time, it allowed for all treatments to experience the same environmental conditions both before and after irrigation.

Not permitting rain water to drain yielded greater storm retention capacity and storage capacity of water after a storm event. When coupled with plants tolerant of flooding conditions, this provided a reservoir of water to sustain plant growth for longer rainless periods. Water was subsequently transpired, permitting greater potential for evaporative cooling and intercepting larger volumes of water before discharge to storm sewers.

Evapotranspiration Rates. During both trials, ET from all treatments eliminated free-standing water within 8 days, with much of the loss occurring in the first 3 days (Figure 2-5). During this time, the evapotranspirative loss from the green roof modules exceeded that of the evaporation pan. Crop coefficients (the ratio comparing the actual of water loss by vegetation to evapotranspiration by an evaporation pan) averaged 3.9 and 3.8 for *Solidago* and 3.4 and 3.4 for *Spartina* during Trials 1 and 2, respectively. The rate of daily water loss via ET decreased thought both trials (Figure 2-5), suggesting that both species would acclimate to a range of water availability by reducing ET rates.

Daily ET declined over the course of each trial as the media moisture was depleted. The counterintuitive finding that a marsh plant had a lower ET rate than an old field colonizer is logical within the context of *Spartina*'s slower growth and lower leaf area. Though *Spartina* ET was consistently lower than *Solidago* ET, there was no significant difference between these two species (Table 2-2). As the *Solidago* bins became drier due to higher ET rates in the first few days of the trial, the overall water consumption of the *Spartina* remained high enough to result in similar total water loss for both plants over the span of the trials. Both selections appeared capable of attenuating rain events approximating a 2 year storm, and eliminating standing water within a few days. Which plant may be ideal depends on selection criteria and weather conditions; *Solidago* may be able to handle storms at greater frequency, while *Spartina* may be able to survive longer in between rain events, at least in considering the first season's growth. We would predict that a mature stand of *Spartina* would support greater ET than an equivalent stand of *Solidago* considering physiological differences, and further study is necessary. In either case, the differences between these two selections are small in comparison to more traditional green roof systems, which do not retain water to the point of saturation.

To relate our ET rates to that of a more traditional green roof system, we compared recently published data on Sedum (VanWoert et al., 2005a) with ours. In the study, Sedum spp. in 2 to 6 cm of green roof growing medium were watered at different intervals (2, 7, 14, 28 and 88 days between watering) to test plant survival and growth as well as ET. While the tests were conducted with shallower medium depths in a greenhouse, with reduced temperatures and no impact from wind, the experimental design approximates a common green roof system. Because the units were freely draining, volumetric water content never exceeded .25 m3*m-3 in the 2 day watering regime, nor above .2 m3*m-3 in any of the others. Freely draining units are common to most green roofs, and would be required for Sedum spp. as it does not tolerate wet conditions. In comparison, the system we used reached maximum water holding capacity at or above .5 m3*m-3, and in the 9 days between watering most treatments remained above .2 m3*m-3. The increased capacity of our system contains greater volumes of water, in addition to the higher medium moisture allowing for greater variety in plant selection for green roof applications, which would not be possible in a freely draining system with a shallower growing medium.

The Sedum study also examined ET rates of the different watering frequencies. In the 2 and 7 day watering schemes, ET peaked at 5 mm*d-1, with little to no ET by day 4 of no irrigation. These figures, while conservative due to the relatively benign greenhouse conditions, are an order of magnitude less than the rates seen in our study. In addition, a Sedum system intended to grow without any irrigation would require irrigation every other day in order to maintain even this modest ET rate. Perhaps plant survival can be attained with the shallow medium and Sedum approach, but the water-related benefits of the green roof are certainly not optimized with this system.

These findings indicate the zero discharge system can both contain a 2-year storm event (76.2 mm) and also quickly dissipate any resulting standing water. Storms in rapid succession should be within the system's capacity to process while allowing no runoff or through flow. By selecting plants that can tolerate a range of medium moisture contents, these plants were capable of maintaining sustained growth during drier periods as well as surviving through extremely wet conditions.

Urban watersheds are in great need of innovation to deal with many water related issues that arise from densely populated and highly impervious areas. Possibilities abound to utilize the roofscape as an actively functioning watershed, as both catchment and sink. As has often proven true in design and engineering, as green roof technology moves closer to mimicking a natural system, the closer it can come to achieving ecological functions and benefits. Green roofs designed to catch and fully utilize water across the growing season provide greater possibilities to reap such benefits.

Conclusion

Current green roof design and testing methods fail to explore systems that maximize storm water retention and evaporative cooling benefits that are often associated with green roofs. The system studied in this experiment utilized no-discharge water holding capacity coupled with native plants capable of high rates of ET and tolerance of flooding. These plants were also able to survive long periods without rainfall, as the volume of water available was increased and prolonged by storing rainfall events within the system. Higher storage capacity also allows for greater plant variety through less extreme drought conditions. Further research is needed to test this concept, and to examine the possibility of supplemental irrigation via off-season rainwater catchment or grey water irrigation.

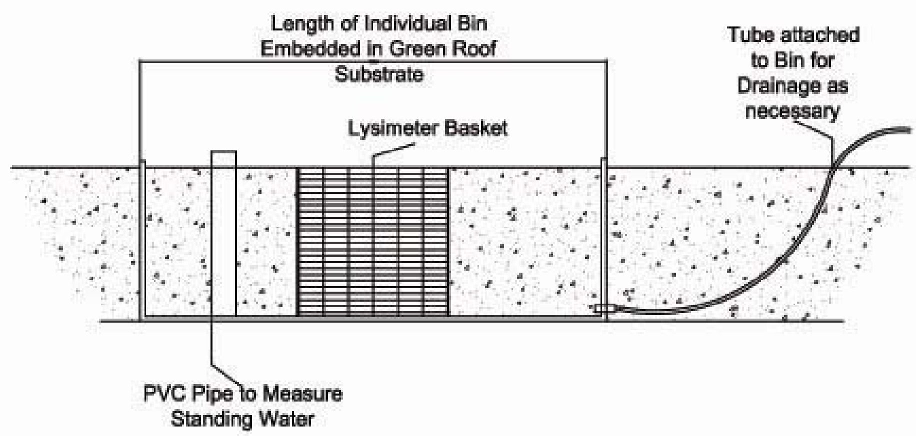

Figure 2-1: Diagram of an individual bin cross-section, indicating the placement of the PVC tube for standing water measurements, as well as the two stacked lysimeter baskets

Figure 2-2: Sample bin, displaying lysimeter basket, PVC tube for reading water height and filter fabric, with Solidago canadensis

Figure 2-3: Two Rows of Bins, with Weather Datalogger, Rain bucket, and evaporation pan in the background (Photo facing East)

Figure 2-4: Volume of Water Added in Trial 1 (Saturation) and 2 (2 Year Storm or Saturation) in Comparison with a 2-year Storm Event (3 inches within 24 hours)

Treatments are Divided by Soil and Species

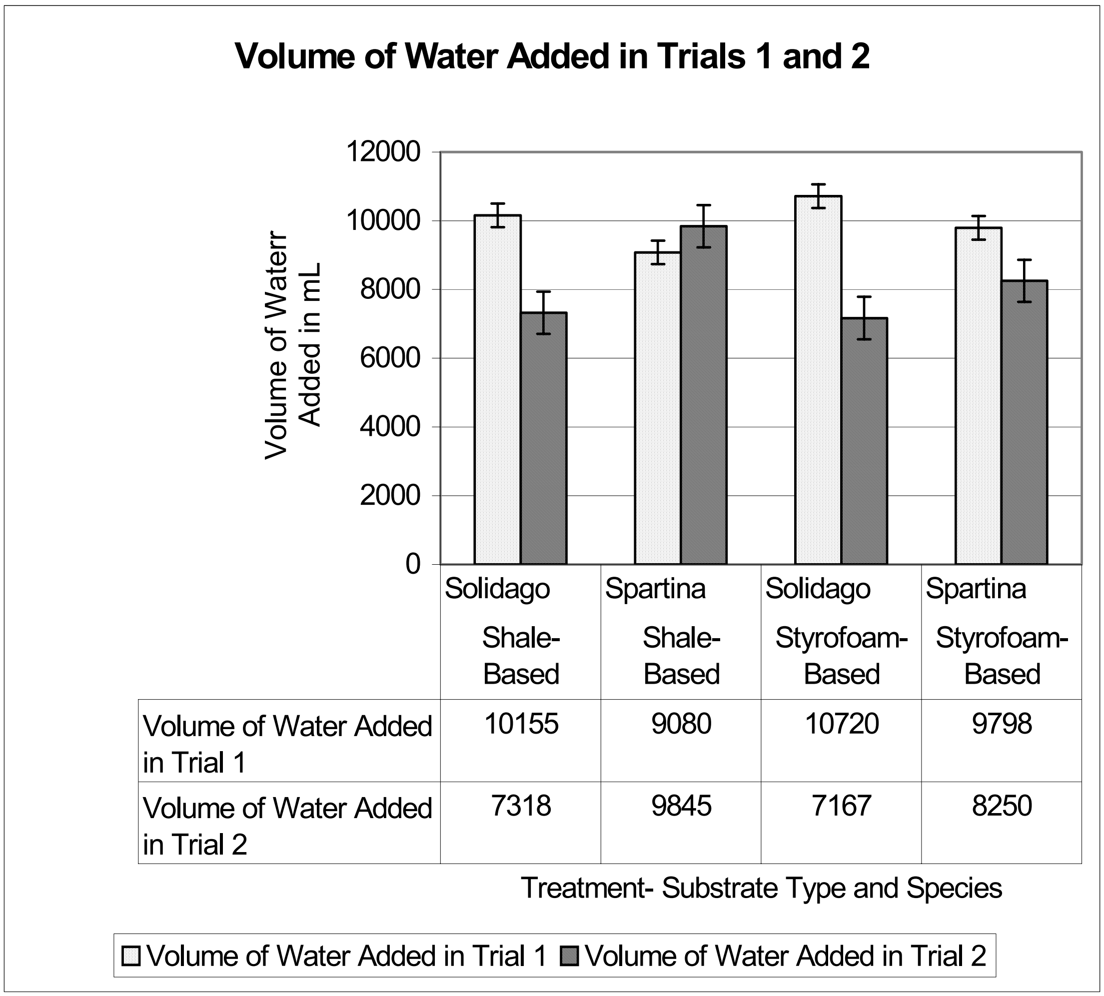

Table 2-1: Analysis of Variance for Volume of Water Added to Bins During Trial 1 (Saturation) and Trial 2 (3" Storm or Saturation) by Substrate, Species, and Substrate x Species

Response Volume Added in 2-Year Storm					
Analysis of Variance					
Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Model	3	8485700	2828567	5.2329	0.0079
Error	20	10810633	540532		
C. Total	23	19296333			
Effect Tests					
Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Substrate	1	1	2470416.7	4.5703	0.0451
Species	1	1	5980016.7	11.0632	0.0034
Substrate*Species	1	1	35266.7	0.0652	0.801

Response Volume Added to Saturation					
Analysis of Variance					
Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Model	3	27249233	9083078	1.1786	0.3429
Error	20	154139167	7706958		
C. Total	23	181388400			
Effect Tests					
Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Substrate	1	1	4576267	0.5938	0.45
Species	1	1	19548150	2.5364	0.1269
Substrate*Species	1	1	3124817	0.4055	0.5315

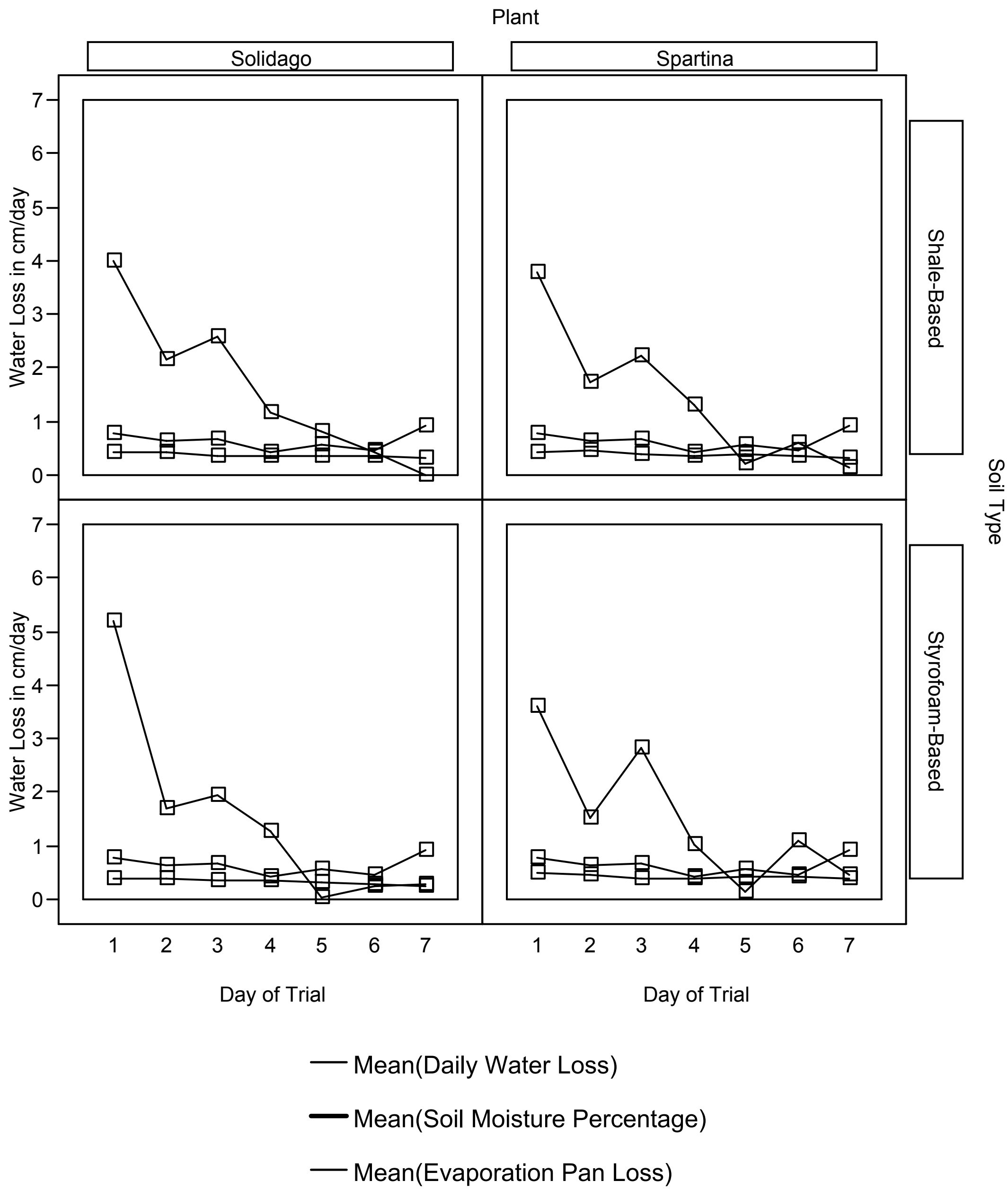

Figure 2-5: Daily Water Loss as Compared with Evaporation Pan Water Loss and Soil Moisture Content in Trial 1

(Trial 2 had similar conditions and results)

Table 2-2: Analysis of Variance for Mean Daily Water Loss During Trial 1 (Saturation) and Trial 2 (3" Storm or Saturation) by Substrate, Species, and Substrate x Species

Response Trial 1 Mean Daily Water Loss					
Analysis of Variance					
Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Model	3	0.0701	0.0234	0.6324	0.6027
Error	20	0.7392	0.0370		
C. Total	23	0.8094			
Effect Tests					
Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Substrate	1	1.0000	0.0099	0.2679	0.6104
Species	1	1.0000	0.0132	0.3567	0.5571
Substrate*Species	1	1.0000	0.0470	1.2726	0.2726

Response Trial 2 Mean Daily Water Loss					
Analysis of Variance					
Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Model	3	0.0242	0.0081	0.3990	0.7552
Error	20	0.4040	0.0202		
C. Total	23	0.4282			
Effect Tests					
Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Substrate	1	1.0000	0.0031	0.1520	0.7008
Species	1	1.0000	0.0082	0.4046	0.5320
Substrate*Species	1	1.0000	0.0129	0.6403	0.4330

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CHAPTER THREE

SOIL AND LEACHATE CHARACTERISTICS OF TWO GREEN ROOF SUBSTRATES

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Abstract

In green roof design, growing media are required to support plant growth despite shallow depths and light weight requirements. Additionally, green roofs are expected to prevent runoff contamination, as they are considered "Best Management Practice" for storm water. Through testing of two substrates, one based on expanded shale and the other a blend with shredded polystyrene, these characteristics were tested. In nutrient analysis and field trials, both substrates proved capable of supporting plant growth at a depth of 15 cm (6 in). Leachate from both substrates contained nitrogen in the form of nitrate and ammonium, but at levels below stringent drinking water standards.

Introduction

Green roof substrates have many demands placed upon them. Loading limits of buildings make extremely lightweight soil necessary, even with very lightweight media. Additionally, the depth of the substrate is limited by cost (Boivin et al., 2001; Nektarios et al., 2003; Tsiotsiopoulou et al., 2003; Lando, 2004; VanWoert et al., 2005). In turn, this places limits on water holding capacity and plant growth, making an ideal media capable of holding high volumes of water in relation to its volume.

Further, the substrate must find a more delicate balance between providing sufficient nutrients to plants and retaining nutrients from storm water runoff.

Storm water is a known contributor of contaminants to waterways, especially in the form of nitrogen and phosphorus (N and P) (Moran et al., 2004; Rushton, 2001). Its management, however, has changed over the past few decades to include "Best Management Practices," which allow for improved storm water retention and recharge into ground water (Moran et al., 2005). Many of these mechanisms allow for the filtration of contaminants (Rushton, 2001; Yu et al., 2001). Such techniques, however, require a certain amount of land area to function. Green roofs have recently become popular for their ability to contend with storm water, especially in metropolitan areas were the space needed for other methods of storm water treatment are not available (Moran et al., 2004). Green roofs are considered capable of retaining storm water on site as well as reducing and delaying the peak flows of runoff. While research has begun testing the green roof's impact on runoff volume and peak flows (Hutchinson et al., 2003; Rowe et al. 2003; Dvorak, 2004; Carter and Rasmussen, 2005; LaBerge et al., 2005; VanWoert et al., 2005), few studies monitor the quality and content of this runoff. However, with problematic N and P contamination in urban areas, the contribution of green roof runoff to contamination warrants examination; be it from atmospheric deposition or green roof substrate. The potential of a green roof to remove contaminants is an important factor in considering them for use in storm water control. Further, the levels of N and P found in its runoff should be considered in comparison to other sources of runoff.

The testing of green roof runoff contents has yielded mixed results. Studies show that N and P levels in runoff for green roofs are not significantly higher than runoff from standard roofs. Moran et al. (2004, 2005) found higher concentrations of N and P in green roof runoff than in rainwater. While the levels from the control roof runoff were lower than the green roof, they were not statistically significant. Often, the variable of substrate composition is a factor in the difference between runoff contents, and altering the organic content of a substrate can reduce the amount of N and P found in runoff (Moran et al., 2004). While the green roof appears to add N and P to the runoff, the study hypothesizes that this will decrease over the life of the green roof. In addition, while the levels of N and P found in green roof runoff were higher than in the rainwater, overall the concentrations remained quite low. N never reached a concentration of 7 mg/l, and phosphorous remained below 1.6 mg/l. It is important to be aware of the risk posed by elevated leachate concentration of these problem elements; however these levels remained within drinking water standards (EPA, 2002).

Materials and Methods

Test Site. The study was conducted on top of a four story school building (St. Simon Stock School) in the South Bronx, New York City. A 3,500 square foot extensive green roof was installed during the week of June 13, 2005. The Barrett "Greenroof-Roofscape®" assembly was used, consisting of 215 mil Barrett "Ram Tough 250" monolithic rubberized asphalt membrane, polyester reinforcement, SBS (Styrene-Butadiene-Styrene) protection course, extruded polystyrene insulation, root barrier, water retention and drainage mat, and filter fabric. The substrate was comprised of approximately 10 cm of medium containing shredded polystyrene coated with pectin, compost and native clay, with a ratio of 90:10:1 by volume. Compost was mixed from agricultural waste. Atop this was another layer, comprised of bound coconut fiber, jute, and straw matting (American Green), a layer of compost and a layer of shredded wood mulch, combined a thickness of 5 cm. The test site consisted of two rows of fiberglass bins embedded in the green roof medium, with all bins receiving uniform exposure to sun and precipitation.

Planting containers. The tops of the two rows of 30.5 X 47 X 15.25 cm fiberglass tubs were installed level with the top of the medium. Each tub contained a removable lysimeter consisting of a plastic basket 15.25 X 15.25 cm (Aquatic Ecosystems, Apopka, FL) that could be removed for weighing. A length of open bottom, 3/4" Schedule 40 PVC pipe was inserted vertically into each tub as an observation well, permitting measurement of the free water depth. Each bin was lined with filter fabric and installed at a slight angle to allow drainage towards a hole drilled at one end. The hole was drilled and 1/8" x 1/4" Barb male adapter (Aquatic Ecosystems) installed, attached to black flexible vinyl tubing (Aquatic Ecosystems) which was brought to the surface and clamped shut. These permitted drainage if necessary as well as sampling leachate (Figure 2-2).

Plant material. *Spartina alterniflora* and *Solidago canadensis* were randomly assigned to the tubs (Figure 2-3). *Spartina* seed was from coastal New Jersey sources (Pinelands Nursery and Supply, Columbus, NJ) while *Solidago* seed was collected from a native stand in Tompkins County, NY. Seed was spread over the surface of 2" deep flats to achieve a density of ca 2 /cm^2 in 1:1:1 mix; peat, soil, perlite during the 3rd week of March, 2005. Later, the *Solidago* plants were moved to peat pots, 4 plants to a pot. *Spartina* seedlings were planted directly into the tubs from the flats. The bins of *Solidago* each received 9 peat pots, planted directly into the medium.

Planting media. The research portion of the roof consisted of 12 bins with one of two medium-plant combinations assigned to 6 bins (see for more information). The first medium (medium 1) was as described above for the entire roof. The other medium (medium 2) was a standard green roof substrate, consisting of 3/8 inch graded expanded shale (Norlite Corporation, Cohoes, NY), coarse ground Perlite® and agricultural waste compost in a 2:1:1 ratio by volume. Both media were mixed with the same source compost and both were installed with the same bound straw matting, compost and mulch layers as the rest of the roof.

Plant Growth. The progress of plant growth was recorded weekly during the summer of 2005, beginning on June 29th and ending on August 10th. Plant height was estimated by measuring from the base of the plant to the three tallest blades of the *Spartina* and the three tallest *Solidago* plants.

Substrate Testing. Samples of both substrates were taken at the time of planting. The compost used in both of the substrates was taken as a sample separately (Table 3-2, Table 3-3). Testing of the substrates was performed by the Cornell University Nutrient Analysis Laboratory. As the samples of both substrates were highly heterogeneous, large pieces were eliminated in the extraction and digestion so as to acquire the most representative samples. All the results were based on dry weight. Extractable levels of P, K, Ca, Mg, Mn, Zn, Al, as well as NO_3 were determined colormetrically with phloranalysis. Al, Fe, Na, Mg, Ca, P, S, Cd, Co, Cr, Cu, Ni, Zn, Mn, Pb, Ti, V were determined by microwave HNO_3 digestion EPA Method 3051. Organic matter was tested through Loss on Ignition (LOI).

Leachate Testing. Leachate samples were taken from each test bin at the end of the growing season on October 13, after rain had saturated the bins. Samples were tested by the Cornell University Nutrient Analysis Laboratory. Ammonium N (NH_4-N) and nitrate (NO_3-N) were determined colormetrically by stannous chloride reduction phloranalysis.

Results and Discussion

Plant Growth. Plant growth, as recorded by weekly measurements, progressed throughout the growing season. Considering the two species'different growth habits, the difference between their heights in both media is of little importance. However, the differences in plant growth between the two media indicate different success based on media type (Figure 3-1). When comparing the two media across both plants, both substrates appeared to be similar in performance. However, the growth of *Solidago* was greater both weekly and throughout the season in the Styrofoam-based substrate, while *Spartina* performed better in the shale-based substrate. Considering that both substrates had similar nutrient availability, the difference in growth rates could be linked to individual species preference for a growing media type, including factors such as rooting habit as influenced by the structure of the substrate.

Substrate Contaminant Levels. The contents of the compost, as well as the two media used in the green roof test plots, were considerably below standards for compost (Table 3-2). The low levels of available heavy metals made leachate contamination very unlikely.

Leachate Composition. N was tested as both NO_3 (nitrate) and NH_4 (ammonium) for all 24 bins. NH_4 levels were consistently higher than NO_3 levels (Figure 3-2). Additionally, these levels varied by both substrate type and plant species, although this variance has little to no significance (Table 3-4). The differences among substrates can be related to the amount of compost in each substrate mix; the same type of compost was used in both substrates and thus the amount, rather than the composition, would cause the difference. However, the shale-based substrate was 25% compost by volume while the Styrofoam-based media was only 10%. The Styrofoam-based media also had higher levels of N present in its leachate. Further testing of the substrates would yield more conclusive information about what factors impact these differences, but are beyond the scope of this study. In all cases, the levels of N were well below the standard of 10 mg/l of nitrate, based on the Environmental Protection Agency Drinking Water Standards (EPA, 2002), and thus pose little reason for concern regarding storm water contamination. While green roof runoff may not improve rain water quality, any negative impacts on runoff are negligible.

Conclusion

The design of green roof substrate must address the limitations of loading and depth of growing media. In doing so, many substrates employ manufactured light weight components with compost as a source of nutrients. This design must take into consideration its impacts beyond weight, however. Plant growth success, nutrient availability for plant growth, and runoff quality must all be considered and tested. The variable nature of compost leads to a need to test its nutrient characteristics before applying it as a green roof substrate. As compost both supplies nutrients for plant growth and adds nutrients to leachate, there likely exists a need to fertilize for long term green roof performance.

Table 3-1: Substrate Characteristics- Density, Mass at 6" (15cm) typical of green roof installations, Nitrogen Content as NH4 and NO3/NO2, Percentage Moisture and Percentage Solid

Characteristic	Shale Based	Styrofoam Based
Density at Dry (kg/cubic meter)	2.5	0.8
Density at Dry (lbs/cubic foot)	40.3	13.1
Density at Saturation (kg/cubic meter)	4.3	2.8
Density at Saturation (lbs/cubic foot)	68.3	45.4
Mass at 15cm depth Dry (kg/cubic meter)	1.3	0.4
Mass at 6" depth Dry (lbs/square foot)	20.1	6.5
Mass at 15cm depth Saturated (kg/cubic meter)	2.1	2.1
Mass at 6" depth Saturated (lbs/square foot)	34.2	22.7
NH4-N	4.2	3.6
NO3+NO2-N	331.0	244.0
Moisture Percentage	30.3	62.4
Percent Solid	69.7	37.6
Porosity (volume of pore space/volume soil)	0.6	0.5

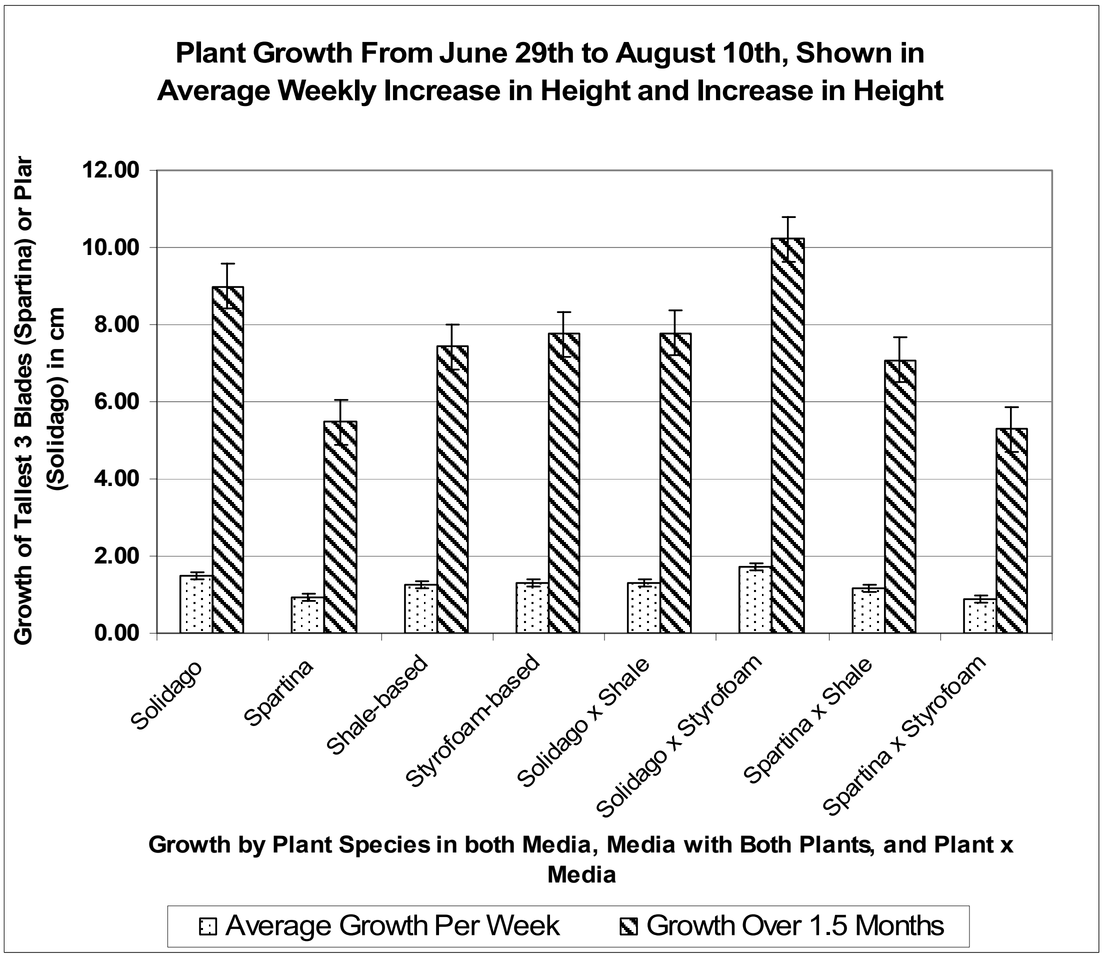

Figure 3-1: Average Plant Growth of Spartina and Solidago shown by plant, by media type, and by plant x media combinations

Table 3-2: Micronutrient availability (mg/kg) in green roof substrates and the compost used in both substrates

Nutrient	Shale Based Soil	Styrofoam Based Soil	Compost
Al	11511	14788	12498
As	4.492	6.748	4.588
B	8.108	8.829	6.311
Ba	86.67	118.57	94.34
Be	0.413	0.599	0.457
Ca	9873	24042	15179
Cd	0.155	1.109	0.221
Co	4.916	7.432	6.828
Cr	13.563	25.931	14.747
Cu	34.980	44.483	38.597
Fe	13705	19308	31588
Hg	<det	<det	<det
K	5240	5065	5413
Li	20.38	20.08	21.74
Mg	5868	13164	6429
Mn	551	732	752
Mo	1.195	0.571	0.830
Na	697	287	264
Ni	14.063	19.339	16.066
P	3092	3600	4323
Pb	14.570	38.188	22.192
S	1632	1969	1746
Sb	0.281	1.741	0.817
Se	3.183	3.214	3.038
Sr	33.48	51.65	48.77
Ti	106.18	206.88	104.52
V	15.175	26.681	15.461
Zn	147.76	208.10	190.57

Contaminant	Compost Guideline Limits		Results from Substrate Testing		
	USEPA Biosolids A/EQ	NYS Class II Compost	Shale Based Soil	Styrofoam Based Soil	Compost
As	<41	41	4.49	6.75	4.59
Cd	<39	10	0.16	1.11	0.22
Cr	n/a	1000	13.56	25.93	14.75
Cu	1500	1500	34.98	44.48	38.60
Fe	n/a	n/a	13705.36	19308.05	31588.27
Hg	17	10	<det	<det	<det
Mo	n/a	40	1.195	0.571	0.830
Ni	420	200	14.06	19.34	16.07
Pb	300	250	14.57	38.19	22.19
Se	100	100	3.18	3.21	3.04
Zn	2800	2500	147.76	208.10	190.57
Source: The Quality of New York State Agricultural Composts Final Report - July 2003, Cornell Waste Management Institute http://compost.css.cornell.edu/APPENDIXH.PDF					

Table 3-3: Heavy Metal Contaminants found in Substrate Soil Tests, in comparison to Environmental Protection Agency Biosolid Compost Standards and New York State Compost Standards

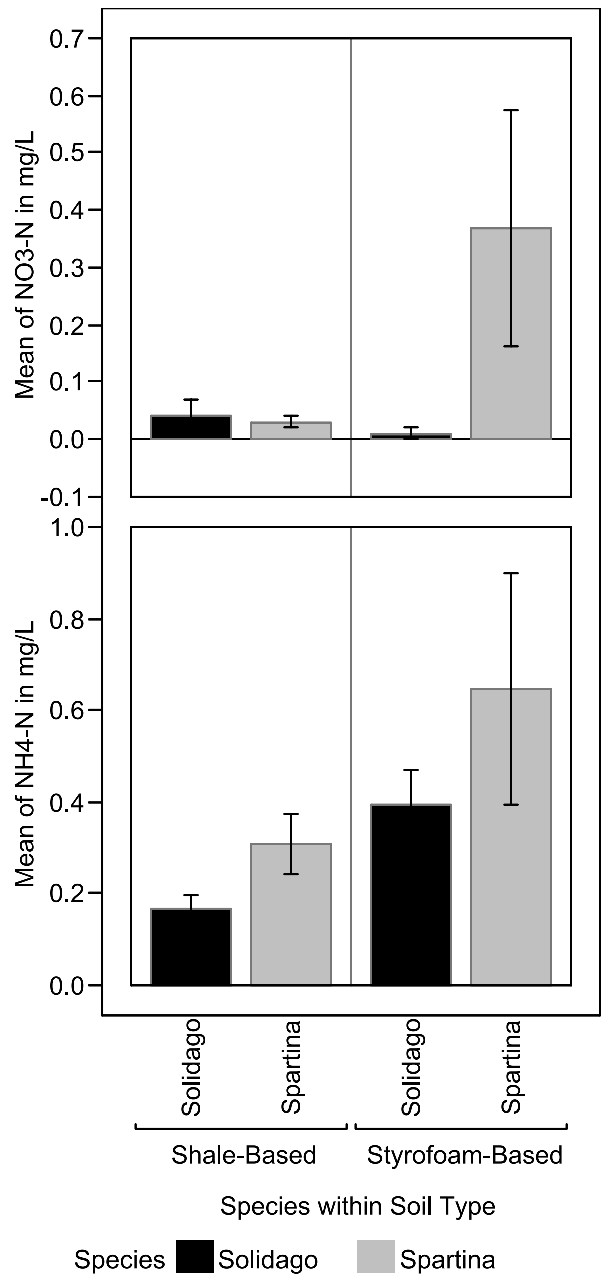

Figure 3-2: Nitrogen Leachate Levels for Two Green Roof Substrates with Two Plant Species

Table 3-4: Analysis of Variance of NO3-N and NH4-N levels in Green Roof Leachate

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Ratio	P Value
ANOVA Test for NO3-N Levels by Soil, Species and Soil x Species					
Model	3	0.5253	0.1751	2.6569	
Soil Type	1	0.1395		2.1174	0.1612
Species	1	0.1785		2.7092	0.1154
Soil Type*Specie	1	0.2072		3.1442	0.0914
Error	20	1.3180	0.0659	0.0762	
C. Total	23	1.8433			
ANOVA Test for NH4-N Levels by Soil, Species and Soil x Species					
Model	3	0.7285	0.2428	2.1985	
Soil Type	1	0.4760		4.3097	0.0510
Species	1	0.2321		2.1011	0.1627
Soil Type*Specie	1	0.0204		0.1848	0.6718
Error	20	2.2090	0.1105	0.1198	
C. Total	23	2.9375			

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APPENDIX

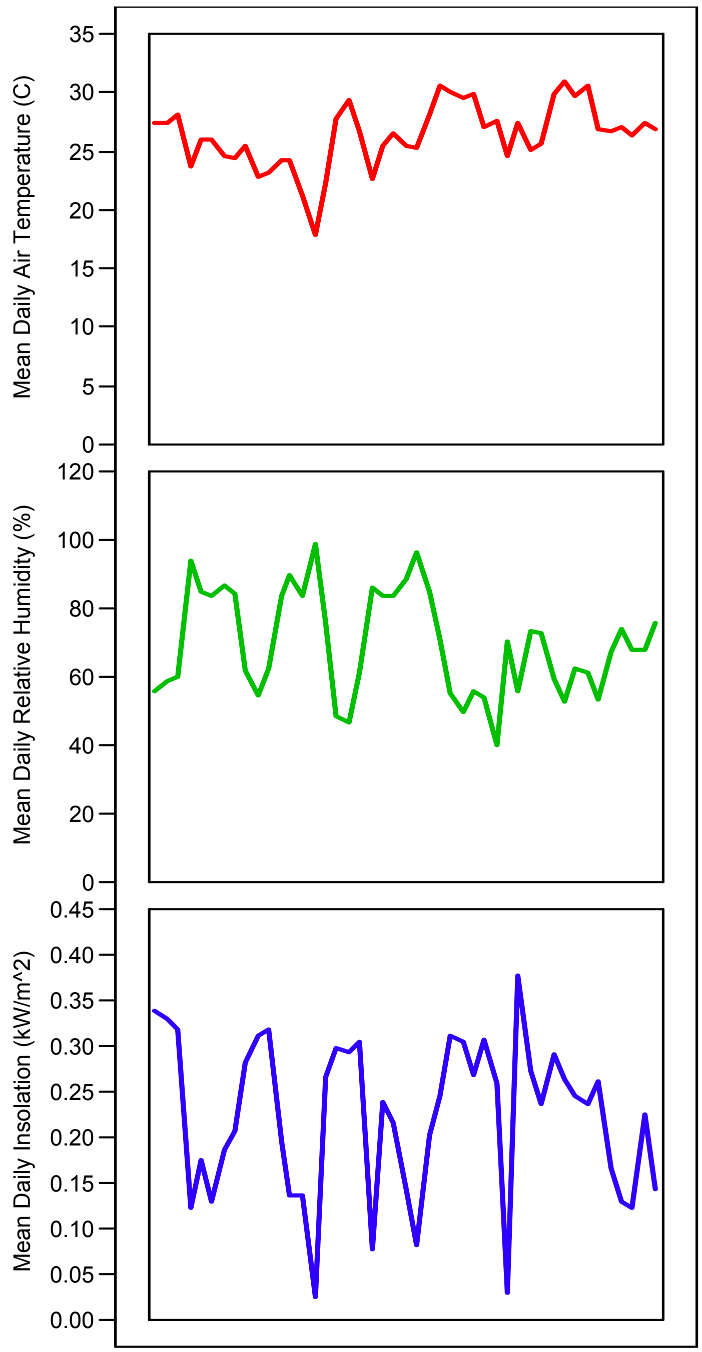

Figure 3-3: Weather Conditions Recorded on the Green Roof During the Course of the Study, Shown as Daily Averages

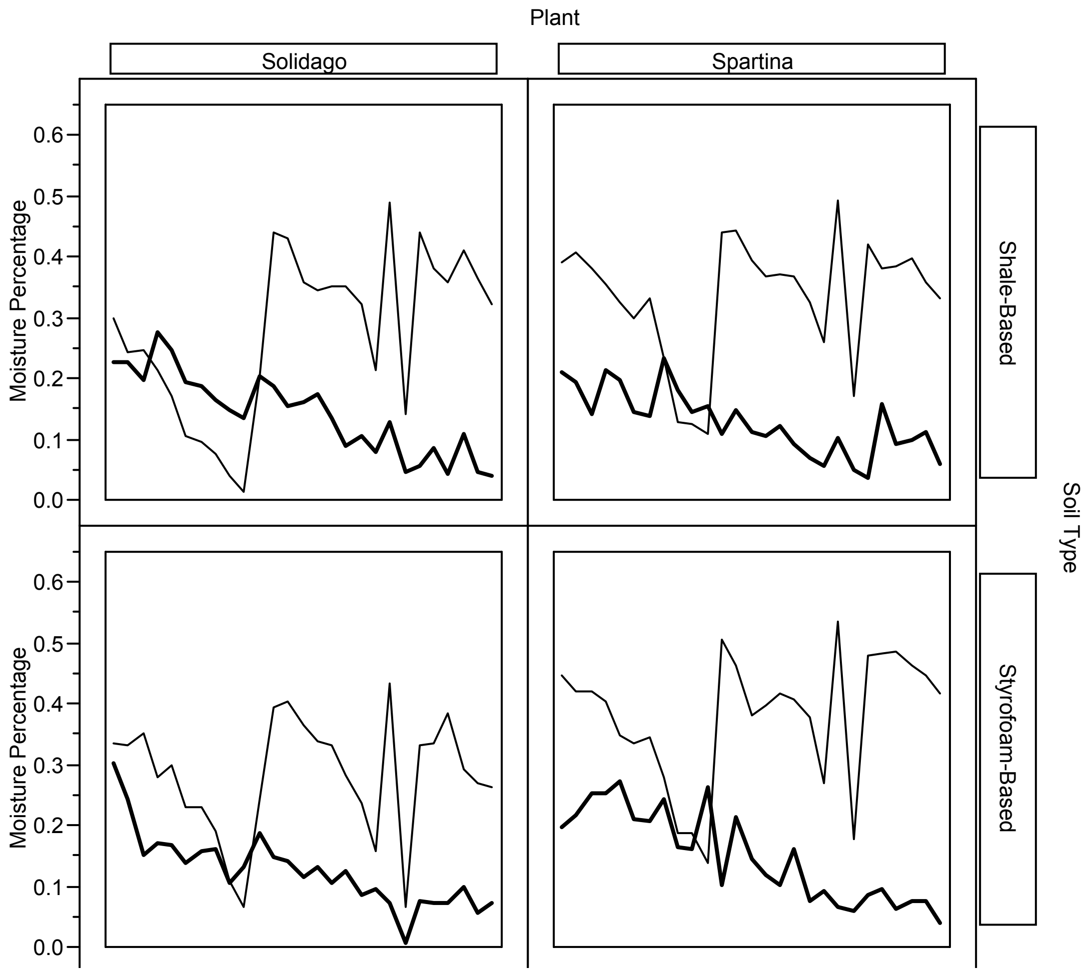

Figure 3-4: Moisture Content as a Percentage of Substrate Volume over the Course of a Month of Testing Period, July 13th-August 12th, Shown for all Test Treatments and the Average of the Substrate Surrounding the Bins